

## HYDRODYNAMICS AND MASS TRANSFER IN UNIFORMLY AERATED BUBBLE COLUMN REACTORS

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Conditions of stable, uniform gas distribution were studied in bubble-type reactors with sieve plates and the effect of geometric parameters of distributing plates and physical properties of liquid phase on the character of the uniformly bubbled bed and on its porosity was considered. Critical velocity in the holes of the plate corresponding to the onset of stable performance of distributing plates has been found to be a function of hole diameter and physical properties of phases. A simple semiempirical relation for the estimate of ranges of stability of sieve plates has been verified on basis of experimental data. Under the conditions of stable uniform gas distribution two differing bubbling regimes were observed in all studied gas-liquid systems. In the region of "homogeneous" bubbling regime the gas holdup has been at comparable conditions in all cases significantly greater than in the "turbulent" regime. Experimental data of volumetric liquid-side mass transfer coefficient  $k_L a$  have demonstrated suitability of the "homogeneous" bubbling regime for obtaining an intensive interphase contact in the bubbled bed.

In recent years there has been a rising interest in application of bubble column reactors for chemical and biological processes in the gas-liquid or gas-liquid-solid systems. This interest has initiated a number of theoretical and experimental studies aimed at obtaining numerous information on various aspects of operation of these units. In our Institute hydrodynamics of bubble column reactors with sieve plates as gas distributors has been studied recently. An attention has been paid namely to the effect of gas distribution on the character of the gas-liquid bed formed in the reactor and on its characteristic hydrodynamic parameters — gas holdup ( $\epsilon_G$ ) and volumetric mass transfer coefficient ( $k_L a$ ). The ultimate goal is to obtain data for design of such plate distributors with which the largest intensity of interfacial mass transfer can be reached under specific operating conditions so that reactors of this type having an advantage in their constructions simplicity and energetic economy could be used even for such chemical or biological processes whose overall rate is significantly affected by the rate of mass transfer between phases. This study has resulted from the long-term program and is directly related to the results of preceding studies which were already published<sup>1-3</sup>. The positive effect of uniform gas distribution on  $\epsilon_G$  and  $k_L a$  has been experimentally verified in these studies and conditions of stable operation of distributing sieve plates have been characterized, which is the pre-condition of formation of a uniform bubble bed. Two different bubbling regimes were observed in the air-water system in the region of stable uniform bubbling whose areas of occurrence were determined by values of gas velocity and of geometric parameters of plates<sup>3</sup>. The gas holdup in the "homogeneous" bubbled bed\* was considerably larger than in the "turbulent" bubbling regime which is usually

\* The term "foam" bubbling regime was used for these conditions in our recent study<sup>3</sup>.

observed in bubbled reactors. Both bubbling regimes differed also by the magnitude of the effect of distributing plate geometry on the character of bubble bed and on corresponding values  $\varepsilon_G$ .

It was the aim of this study to complete and generalise this present knowledge with the regard to the above stated goal-formulation of principles for the design of an optimal distributing plate. The main objective of this study was determination of the effect of physical properties of the liquid phase and its ability to support or hinder coalescence of bubbles in the bed on the range of stable operation of plates, on the existence of two bubbling regimes observed in the water-air system (and eventually on conditions or regions of their existence) and on magnitude of the gas holdup in the bed. Another aim of this study was to consider on basis of experimental  $k_L a$  data the effect of the bubbling regime on intensity of interfacial mass transfer in the bed and to compare the relation between  $k_L a$  and gas holdup for both bubbling regimes.

## EXPERIMENTAL

The experiments were performed in a single stage bubble column with the diameter 0.152 m. Distributing plates were made of brass sheets of thickness 0.003 m and holes were situated uniformly on the whole area in a triangular pitch. The hole diameters of plates used ranged between 0.5 and 3 mm and free plate areas between 0.2 and 1%. Survey of plates used and of their geometric parameters is given in Table I. The experiments were performed under the zero liquid flow rate with constant liquid holdup in the bed. Ratio of the clear liquid height to the reactor diameter ( $H_0/D_K$ ) was in all cases equal to seven. Superficial gas velocities were within the range 0.009–0.276 m s<sup>-1</sup>. In Table II is given the survey of used gas-liquid systems and the corresponding physical properties of phases. Air was used as the gas phase in all cases. Determination of the limits of stable plate operation and measurements of gas holdup in the uniformly bubbled bed were performed for three liquid phases—*n*-butanol, aqueous solution of acetone (40% by mass) and aqueous solution of ethanol (1 vol.%). For comparison data for the water-air system obtained in our recent study<sup>3</sup> are also included among the results. The  $k_L a$  values were measured only in the water-air system.

Critical gas velocities in the holes of the plate were determined on basis of the visual estimate of the number of bubbling holes on the plate<sup>3</sup>, gas holdup was measured by the method of pressure differences<sup>4</sup>. The  $k_L a$  values were determined by the dynamic method by evaluation of the response of the oxygen probe on saturation of the liquid in reactor by air oxygen. For measurement of the polarographic probe of the Clark type was used (Research workshop of the Czechoslovak Academy of Sciences) with the teflon membrane of thickness 0.015 mm. At evaluation of the probe response ideal mixing of the liquid phase has been assumed, for description of the probe dynamics has been used the two-region model proposed by Linek<sup>5</sup>.

## RESULTS AND DISCUSSION

### *Conditions of Stable Operation of Distributing Plates*

Boundaries of stable plate operation are characterised by certain critical values

of pressure drop above which the plate operation is not affected by pressure fluctuations in the bed, *i.e.* the gas distribution is independent of the dynamics of the bubbled bed<sup>3</sup>. For the given plate (characterised by values of the hole diameter and free plate area) and for the specific two-phase system corresponds to this limiting value of pressure drop a critical value of gas velocity in the plate holes  $u_{0,crit}$ . The values  $u_{0,crit}$  measured for individual gas-liquid systems are summarised in Table III.

TABLE I  
Parameters of distributing plates

$d_0$ , mm	$t/d_0$	$\varphi$ , %	$n$	$\eta$ , m <sup>-2</sup>
0.5	6	0.2	190	10 500
1.0	3	0.2	47	2 597
		0.5	113	6 243
		1.0	228	12 600
1.6	1.875	0.2	19	1 050
		0.5	45	2 486
		1.0	92	5 083
3.0	1	0.2	5	276
		0.5	13	718
		1.0	26	1 436

TABLE II  
Gas-liquid systems studied and their physical properties at 20°C;  $\rho_G = 1.21$  kg/m<sup>3</sup>,  $\mu_G = 1.81 \cdot 10^{-5}$  Ns/m<sup>2</sup>

System	$\rho_L$ kg/m <sup>3</sup>	$\mu_L \cdot 10^3$ Ns/m <sup>2</sup>	$\sigma \cdot 10^3$ N/m	$t$ °C
Air-water	1 000	1.01	72.8	20
Air-butanol	814	2.89	24.6	20
Air-acetone sol. in water (40 weight %)	940	1.57	33.3	20
Air-ethanol sol. in water (1 vol. %)	998	0.93	57.2	25

From this Table is obvious the effect of liquid phase properties and hole diameters on the values of  $u_{0,crit}$ . In agreement with the definition the experimentally determined values of  $u_{0,crit}$  are independent of the free plate area. In Table IV are given

TABLE III  
Critical values  $u_0 = w_G/\phi$

$d_0$ mm	$\phi$ %	$u_{0,crit}, \text{m s}^{-1}$			
		Air-water	Air-butanol	Air-acetone sol.	Air-ethanol sol.
3	0.2	6.15	4.6	5.4	3.85
	0.5	6.2	4.6	6.2	3.7
	1.0	7.7	4.6	6.1	4.6
1.6	0.2	10.75	6.15	9.2	6.9
	0.5	10.8	6.4	9.2	6.8
	1.0	10.7	6.1	9.2	7.1
1	0.2	12.3	7.7	12.3	9.2
	0.5	12.2	7.7	12.2	9.2
	1.0	12.3	7.7	12.3	9.2
0.5	0.2	15.35	10.7	15.35	12.3

TABLE IV  
Critical values  $We_{0,crit} = u_{0,crit}^2 d_0 \rho_G / \sigma$

$d_0$ mm	$\phi$ %	Air-water	Air-butanol	Air-acetone sol.	Air-ethanol sol.
3	0.2	1.9	3.1	1.8	1.6
	0.5	1.9	3.1	2.4	1.5
	1.0	3.0	3.1	2.4	2.3
1.6	0.2	3.1	3.0	2.9	2.8
	0.5	3.1	3.2	2.9	2.7
	1.0	3.0	2.9	2.9	2.9
1	0.2	2.5	2.9	3.2	3.1
	0.5	2.5	2.9	3.1	3.1
	1.0	2.5	2.9	3.2	3.1
0.5	0.2	2.0	2.8	2.5	2.7

the corresponding critical values of the Weber number related to the diameter of the plate hole<sup>5</sup>

$$We_{0,crit} = u_{0,crit}^2 d_0 \rho_G / \sigma. \quad (1)$$

It is obvious that the Weber number defined in this way well expresses the effect of individual variables ( $d_0, \sigma$ ) on  $u_{0,crit}$  and the operation of plates can be in all cases considered to be stable for  $We_0 \leq 3$ . Mersmann<sup>6</sup> has theoretically predicted the value  $We_{0,crit} = 2$ , Gerstenberg<sup>7</sup> gives as the limit of stable bubbling the value  $We_0 = 4$ . For large hole diameters ( $d_0 \geq 3$ ), with regard to the danger of weeping, it is recommended to operate at larger values of  $u_0$  than corresponds to the corresponding critical value of the Weber number. Mersmann<sup>6</sup> gives for determination of the limiting value  $u_0$  in these cases the condition  $Fr_0 \geq 0.37$ . Froude number related to the conditions in the holes of the plate is defined by relation

$$Fr_0 = [\rho_G / (\rho_L - \rho_G)]^{1.25} (u_0^2 / d_0 g).$$

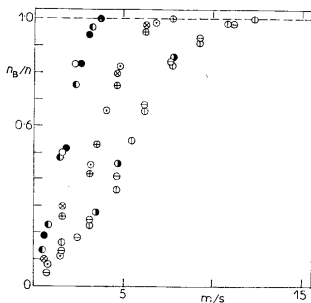


FIG. 1

Effect of relative free plate area on dependence  $n_B/n$  on  $u_0$  for acetone sol.-air ( $d_0 = 3$  mm)  $\circ$   $\varphi = 0.2\%$ ,  $\bullet$   $\varphi = 0.5\%$ ,  $\ominus$   $\varphi = 1.0\%$ ; ethanol sol.-air ( $d_0 = 1$  mm)  $\circ$   $\varphi = 0.2\%$ ,  $\ominus$   $\varphi = 0.5\%$ ,  $\omin�$   $\varphi = 1.0\%$ ; butanol-air ( $d_0 = 1.6$  mm)  $\oplus$   $\varphi = 0.2\%$ ,  $\otimes$   $\varphi = 0.5\%$ ,  $\odot$   $\varphi = 1.0\%$

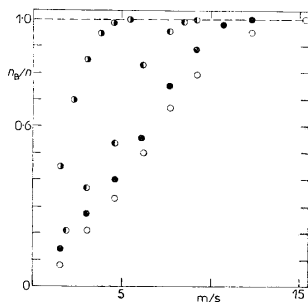


FIG. 2

Effect of hole diameter on dependence  $n_B/n$  on  $u_0$  for ethanol sol.-air,  $\varphi = 0.2\%$   $\circ$   $d_0 = 0.5$  mm,  $\bullet$   $d_0 = 1$  mm,  $\omin�$   $d_0 = 1.6$  mm,  $\omin�$   $d_0 = 3$  mm

The effect of plate geometry on the form of dependence of the number of bubbling holes on the gas velocity related to the area of plate holes ( $n_b/n$  vs  $u_0$ ) is demonstrated for individual measured systems in Figs 1 and 2. The shape of dependences and the observed effect of geometric plate parameters was for all systems similar as for the water-air system<sup>3</sup>. For none of the measured systems has been found any effect of the free plate area on the shape of this dependence (Fig. 1) and the observed effect of  $d_0$  (Fig. 2) corresponded to the effect of this parameter on the value of  $u_{0,crit}$ .

#### *Effect of Plate Geometry on Character of Uniformly Bubbled Bed*

Values of gas holdup ratio were measured and the character of the bubbled bed was studied visually in all systems considered under the conditions of stable uniform gas distribution. Similarly as earlier in the water-air system, the existence of the regime of "homogeneous" bubbling was observed in all three systems studied, in the region of low and medium gas flow rates on plates with large concentration of small diameter holes. Range of existence of this regime was however different for individual systems and similarly was found for individual systems different effect of the existence of this regime on gas holdup in the bed. For the system air-butylalcohol and air-aqueous solution of acetone, the "homogeneous" bubbling was observed only on the plate with the hole diameter 0.5 mm ( $\varphi = 0.2\%$ ), for the systems air-water and air-aqueous solution of ethanol this regime existed also on plates with the hole diameter 1 mm (at  $\varphi = 0.5$  and  $1\%$ ). Similarly, ranges of values  $w_G$  in which existed the regime of "homogeneous" bubbling on individual plates were different. In Fig. 3 is plotted for all four systems gas-liquid the dependence  $\varepsilon_G$  on  $w_G$  for plates with  $\varphi = 0.2\%$ ,  $d_0 = 0.5$  mm. From this figure it is obvious that in individual systems differs both the range of  $w_G$  corresponding to the existence of the "homogeneous" bubbling as well as the coordinates of the maximum on the dependence  $\varepsilon_{G,max} - w_{G,max}$ .

In Tables V and VI is also given comparison of gas holdups for the regions of "homogeneous" and "turbulent" bubbling regime. In Table V are given the extreme values  $\varepsilon_{G,max} - w_{G,max}$  corresponding to the fully developed regime of "homogeneous" bubbling on the plate  $\varphi = 0.2\%$ ,  $d_0 = 0.5$  mm and the corresponding data  $\varepsilon_G - w_G$  (for values  $\varepsilon_G \approx \varepsilon_{G,max}$ ) obtained on the same plate at the conditions of "turbulent" bubbling. The comparison demonstrates that in the "homogeneous" bubbling regime comparable porosity values can be obtained at significantly lower gas velocities than in the case of "turbulent" regime.

In Table VI are given porosity data which were obtained on plates with equal free area but differing by the value  $d_0$  and thus operating at the given gas velocity in the region of "homogeneous" or "turbulent" bubbling. Results of this comparison are again favourable for the "homogeneous" bubbling regime and it is thus obvious that for obtaining a large gas holdup and thus also large interfacial area it is preferable

to operate in the region of „homogeneous” bubbling. The mass transfer intensity in the bed is however characterised by the volumetric mass transfer coefficient  $k_L a$ . For final evaluation of the effect of “homogeneous” regime on the mass transfer intensity it has been thus necessary to find out if the increase of gas holdup in the region of “homogeneous” bubbling is accompanied by the corresponding increase of  $k_L a$  as it is usual in the “turbulent” region in which the dependence of both quantities can be described by a definite functional relation<sup>8</sup>.

TABLE V

Maximum porosity for regimes of “homogeneous” and “turbulent” bubbling for  $D_K = 0.152$  m;  $d_0 = 0.5$  mm;  $\phi = 0.2\%$

System	Homogeneous regime		Turbulent regime	
	$w_{G,max}$	$\varepsilon_{G,max}$	$w_G$	$\varepsilon_G$
Water-air	0.092	0.394	0.276	0.339
Butanol-air	0.038	0.176	0.061	0.173
Acetone sol.-air	0.046	0.282	0.153	0.275
Ethanol sol.-air	0.092	0.481	0.276	0.379

TABLE VI

Comparison of experimental porosities at “homogeneous” and “turbulent” bubbling

System	$\phi$ %	$w_G$ m/s	$d_0$ mm	$\varepsilon_G$	Regime
Water-air	0.2	0.092	0.5	0.394	“homogeneous”
			1.6	0.174	“turbulent”
Butanol-air	0.2	0.038	0.5	0.176	“homogeneous”
			1.6	0.102	“turbulent”
Acetone sol.-air	0.2	0.046	0.5	0.282	“homogeneous”
			1.6	0.165	“turbulent”
Ethanol sol.-air	0.2	0.092	0.5	0.481	“homogeneous”
			1.6	0.228	“turbulent”

Relation between  $k_L a$  and Gas Holdup at Different Bubbling Regimes

The  $k_L a$  values were measured for the water-air system in the whole range of gas velocities and values of geometric plate parameters ( $\varphi$  and  $d_0$ ). The character of the observed dependences of  $k_L a$  on  $w_G$  corresponds qualitatively in the whole measured range of individual variables to the dependence of  $\varepsilon_G$  on  $w_G$ . On plates on which the existence of the homogeneous bubbling regime was found the dependences of  $k_L a$

TABLE VII

Coordinates of extremes on the dependence  $\varepsilon_G - w_G$  or  $k_L a - w_G$  for the regime of "homogeneous" bubbling

$\varphi$ %	$d_0$ mm	$\varepsilon_{G,max}$	$w_{G,max}$ $m\ s^{-1}$	$(k_L a)_{max}$ $s^{-1}$	$w_{G,max}$ $m\ s^{-1}$
0.5	1	0.310	0.092	0.136	0.092
1	1	0.354	0.123	0.173	0.138
0.2	0.5	0.394	0.092	0.169	0.092

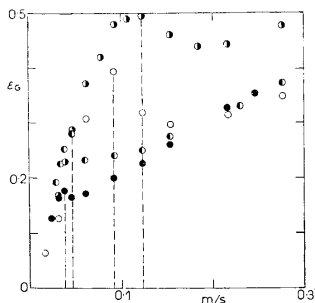


FIG. 3

Gas holdup in dependence on superficial gas velocity  $w_G$  for the regime of "homogeneous" bubbling.  $\varphi = 0.2\%$ ,  $d_0 = 0.5$  mm;  $\circ$  water-air,  $\bullet$  butanol-air,  $\ominus$  acetone sol.-air,  $\omin�$  ethanol sol.-air

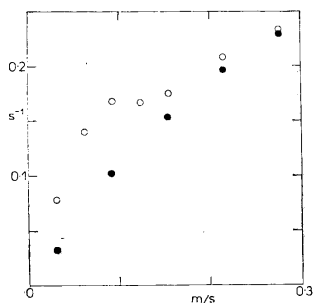


FIG. 4

Comparison of dependences  $k_L a$  on  $w_G$  for the regimes of "homogeneous" and "turbulent" bubbling. System water-air,  $\varphi = 0.2\%$ ,  $d_0 = 0.5$  mm ("homogeneous" bubbling),  $d_0 = 1$  mm ("turbulent" bubbling)



on  $w_G$  had a maximum at values  $w_G$  corresponding to the values of  $w_{G,max}$  in the dependence of  $\varepsilon_G$  on  $w_G$  (Table VII). Values of  $k_{L,a}$  measured at equal gas velocities for the region of "homogeneous" bubbling were significantly higher than for "turbulent" regime (Fig. 4).

In Fig. 5 are simultaneously plotted the dependences of  $k_{L,a}$  on  $w_G$  and  $\varepsilon_G$  on  $w_G$  obtained under the conditions of the "homogeneous" bubbling regime. From this figure it is obvious that the dependence  $k_{L,a} - w_G$  has a similar shape as the porosity dependence but that the effect of "homogeneous" bubbling on increase of  $k_{L,a}$  is not so profound as in the case of gas holdup ratio. This fact can be qualitatively explained by the possible opposite effect of "homogeneous" bubbling regime on  $k_L$  and  $a$ , confirmation of this hypothesis would indeed require performance of simultaneous independent measurements of  $k_L$  and  $k_{L,a}$ .

The obtained data of  $k_{L,a}$  indicate, that at the "homogeneous" bubbling regime relatively large values of  $k_{L,a}$  can be obtained at considerably lower gas velocities than in the region of "turbulent" bubbling. With regard to the fact that plates with the hole diameters  $d_0 \leq 1$  mm are in larger units unpractical both from production and operating reasons it would be useful to test sintered glass or porous metal plates as gas distributors.

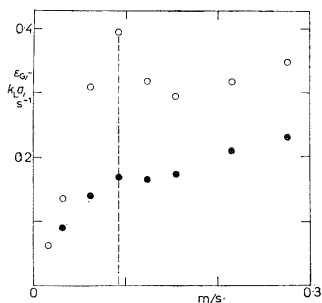


FIG. 5

Comparison of dependences of  $k_{L,a}$  on  $w_G$  and  $\varepsilon_G$  on  $w_G$  for the regime of "homogeneous" bubbling. System water-air,  $\varphi = 0.2\%$ ,  $d_0 = 0.5$  mm,  $\circ$  data  $\varepsilon_G$ ,  $\bullet$  data  $k_{L,a}$

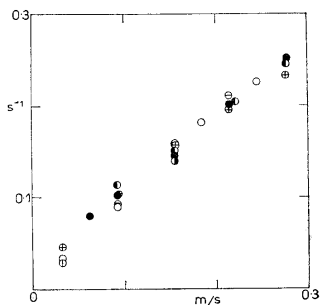


FIG. 6

Dependence of  $k_{L,a}$  on superficial gas velocity  $w_G$  for the regime of "turbulent" bubbling. System water-air;  $\oplus$   $\varphi = 0.2\%$ ,  $d_0 = 1$  mm;  $\circ$   $\varphi = 0.2\%$ ,  $\bullet$   $\varphi = 0.5\%$ ,  $\ominus$   $\varphi = 1.0\%$ ,  $d_0 = 1.6$  mm;  $\oplus$   $\varphi = 0.2\%$ ,  $\ominus$   $\varphi = 0.5\%$ ,  $\bullet$   $\varphi = 1.0\%$ ,  $d_0 = 3$  mm

In Fig. 6 is plotted the dependence  $k_L a$  on  $w_G$  for "turbulent" bubbling regime. Similarly as with the dependence  $\varepsilon_G - w_G$  obtained earlier<sup>3</sup> for this system, no effect of geometry has been manifested. Evaluation of experimental data has revealed, that the data  $k_L a$  measured at turbulent bubbling regime can be correlated by the relation

$$k_L a = \phi D_L^{0.5} \frac{g^{0.25}}{\sigma^{0.6}} \cdot \frac{v_G^{0.65}}{v_L^{0.9}} \cdot \frac{\rho_G^{0.65}}{\rho_L^{0.05}} w_G^{0.65} \varepsilon_G^{0.35} (1 - \varepsilon_G)^{0.65} \quad (2)$$

derived earlier by Kaštánek<sup>8</sup> on basis of the assumption of isotropic turbulence in the liquid phase.

### *Effect of Physical Properties of the Liquid Phase on Gas Holdup in the Bed*

The effect of plate geometry on gas holdup at turbulent bubbling regime was different in individual gas-liquid systems studied in agreement with Schügerl's conclusions<sup>9</sup> on the effect of  $d_0$  on gas holdup in systems with the liquid phase supporting or hindering the coalescence of bubbles in the bed. In the media supporting coalescence such as butanol or water the effect of plate geometry on gas holdup has not ap-

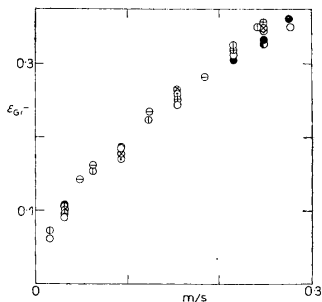


FIG. 7

Dependence of  $\varepsilon_G$  on  $w_G$  in the system with significant coalescence (regime of "turbulent" bubbling). System butanol-air;  $\odot$   $\phi = 0.2\%$ ,  $\ominus$   $\phi = 0.5\%$ ,  $\bullet$   $\phi = 1.0\%$ ,  $d_0 = 1$  mm;  $\omin�$   $\phi = 0.2\%$ ,  $\bullet$   $\phi = 0.5\%$ ,  $\bullet$   $\phi = 1.0\%$ ,  $d_0 = 1.6$  mm;  $\oplus$   $\phi = 0.2\%$ ,  $\otimes$   $\phi = 0.5\%$ ,  $\odot$   $\phi = 1.0\%$ ,  $d_0 = 3$  mm

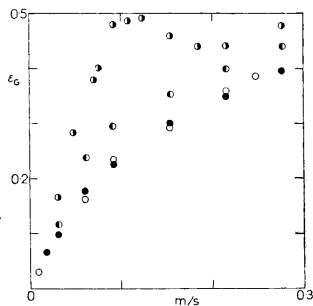


FIG. 8

Effect of hole diameter on dependence  $\varepsilon_G$  on  $w_G$  in the system with suppressed coalescence. System ethanol sol.-air,  $\phi = 0.2\%$ ,  $\circ$   $d_0 = 3$  mm,  $\bullet$   $d_0 = 1.6$  mm,  $\omin�$   $d_0 = 1$  mm,  $\oplus$   $d_0 = 0.5$  mm

peared (Fig. 7). On the contrary, in the ethanol solution, which is a typical example of the medium hindering coalescence a significant effect of  $d_0$  on gas holdup was observed. Experimental data have however proved in agreement with the data of Bach and Pilhofer<sup>10</sup> that this effect is significant only for small holes,  $d_0 < 1.6$  mm (Fig. 8). For  $d_0 \geq 1.6$  mm the values  $\varepsilon_G$  did not depend on the hole diameter which is significant for the modelling of hydrodynamics of large-scale units<sup>11</sup>. For all four systems, the dependence of  $\varepsilon_G$  on  $w_G$  has in the turbulent region the characteristic nonlinear dependence demonstrated in Fig. 9.

For description of this type of dependence in general is recommended the relation

$$\varepsilon_G = w_G / (A + Bw_G) \quad (3)$$

in which the term in the denominator represents the relation between the upward velocity of bubbles with different sizes under the conditions of interference and the superficial gas velocity. The coefficients  $A$  and  $B$  are functions of parameters of the given unit and of properties of the used gas-liquid system and in general it is possible to assume that conditions in an arbitrary bubbled bed can be characterised by a corresponding pair of these coefficients<sup>2</sup>. In our case the relation (3) has been used for correlation of data for gas holdup obtained at turbulent bubbling under conditions when the effect of plate geometry has not taken place. Values of coefficients  $A$  and  $B$  calculated by the least squares method and given in Table VIII are thus characteristic for individual measured gas-liquid systems.

In literature there exists a number of empirical or semiempirical dependences proposed for correlation of the dependence of  $\varepsilon_G$  on  $w_G$  which express in different way the effect of physical properties of both phases. But these relations were usually obtained on basis of measurements in a limited system of compounds representing

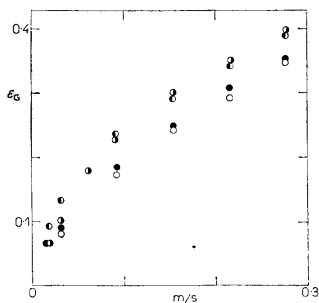


FIG. 9  
Dependence of  $\varepsilon_G$  on  $w_G$  for individual gas-liquid systems (regime of "turbulent" bubbling)  $\phi = 0.2\%$ ,  $d_0 = 1.6$  mm; ○ water-air, ● butanol-air, ⊙ acetone sol.-air, ⊖ ethanol sol.-air

a certain set of compounds of the same type and consequently fail when applied beyond the considered set of gas-liquid systems. For illustration in Table IX is given a comparison of our experimental  $\epsilon_G$  data with values calculated from the frequently recommended relation by Hughmark<sup>12</sup>

$$\epsilon_G = \frac{w_G}{2w_G + 0.3} \left( \frac{\rho_{H_2O}}{\rho_L} \cdot \frac{\sigma_{H_2O}}{\sigma} \right)^{0.33} \quad (4)$$

TABLE VIII

Coefficients  $A$ ,  $B$  (Eq. (3)) calculated from experimental data for individual gas-liquid systems

System	$A$ $m s^{-1}$	$B$
Air-water	0.31	1.97
Air-butanol	0.31	1.74
Air-acetone sol.	0.20	2.00
Air-ethanol sol.	0.28	1.51

TABLE IX

Comparison of experimental and calculated gas holdups for the regime of "turbulent" bubbling

System	$w_G$ $m s^{-1}$	$\epsilon_{G,exp}$	$\epsilon_{G,calc}$		
			Hughmark <sup>12</sup>	Hikita <sup>13</sup>	Kašánek <sup>15</sup>
Air-water	0.031	0.075	0.086	0.101	0.080
	0.092	0.175	0.190	0.190	0.159
	0.153	0.237	0.252	0.256	0.210
	0.215	0.289	0.294	0.311	0.249
Air-butanol	0.031	0.099	0.131	0.116	0.098
	0.092	0.190	0.290	0.218	0.191
	0.153	0.252	0.386	0.292	0.258
	0.215	0.317	0.451	0.355	0.324
Air-ethanol sol.	0.031	0.104	0.092	0.107	0.080
	0.092	0.252	0.205	0.200	0.159
	0.153	0.309	0.272	0.268	0.210
	0.215	0.367	0.319	0.327	0.249

and from the dependence of Hikita and Assai<sup>13</sup> obtained by correlation of an extensive set of experimental data

$$\varepsilon_G = 0.672 \left( \frac{w_G \mu_L}{\sigma} \right)^{0.578} \left( \frac{\mu_L^4 g}{\rho_L \sigma^3} \right)^{-0.131} \left( \frac{\rho_G}{\rho_L} \right)^{0.062} \left( \frac{\mu_G}{\mu_L} \right)^{0.107} \quad (5)$$

It is obvious that these relations do not enable to express the experimental dependence of  $\varepsilon_G$  on  $w_G$ . The reason of that is obviously the fact that the character of bubbled beds and thus also the values of their hydrodynamic parameters do not depend directly on physical properties of phases ( $\rho$ ,  $\mu$ ,  $\sigma$ ) and mechanical correlation of  $\varepsilon_G$  or  $k_L a$  according to these quantities do not represent an adequate description of the actual state. Moreover experimental data published by Bach and Philhofer<sup>10</sup> in agreement with our results, have confirmed that the character of the bubbled bed and thus also values of its hydrodynamic parameters depend on the liquid phase nature *i.e.* they differ in cases when pure liquids or solutions (both solutions of electrolytes or liquid mixtures) are used as a liquid phase. All these experimental data justify the frequently presented assumption that behaviour of the gas-liquid beds is in a decisive manner determined by surface properties of the liquid phase (surface tension, surface viscosity, surface elasticity)<sup>14</sup>. Mechanism of this action has not yet been described either qualitatively or quantitatively. Attempts have been therefore made to correlate gas holdup by means of other characteristic bubble bed parameters including implicitly the effect of surface properties (as *e.g.* Sauter mean bubble diameter,  $d_s$ ) or to derive appropriate relations for  $\varepsilon_G$  on the basis of a theoretical description of bubble bed behaviour. Table IX presents a relatively good agreement of experimental data  $\varepsilon_G$  with the values calculated for systems with pure compounds (water, butanol) used as the liquid phase from the relation derived by Kaštánek, Nývlt and Rylek<sup>15</sup> on basis of the description of pressure drop in the bubbled bed

$$\varepsilon_G = 82 \left( \frac{1}{g} \frac{\rho_G}{\rho_L} \right)^{0.27} \left( \frac{\mu_G}{\rho_G} \right)^{0.2} \left( \frac{\mu_L^{0.1}}{\sigma^{0.035}} \right) \frac{w_G^{0.8}}{(2w_G + 0.2)^{0.47}} \quad (6)$$

Neither this relation enables however determination of gas holdup values for systems with solutions as the liquid phase (Table IX), which can be again ascribed to the insufficient expression of the effect of surface properties of the system on character of the bubbled bed.

Schügerl<sup>9</sup> has proposed for correlation of data on gas holdup in systems with an arbitrary liquid phase (pure liquids and solutions) the relation

$$\varepsilon_G = 0.91 Fr^{1.19}, \quad (7)$$

where  $Fr = w_G/\sqrt{(gd_s)}$ . The quantity  $d_s$  obviously appropriately indicates the character of the bed but its determination is rather questionable due to the lack of a reliable general method for determination of the size distribution in a bubble bed which has to be known for  $d_s$  calculation. It can thus be concluded that at the present time no general reliable relation is available for an *a priori* calculation of gas hold up (and consequently also of  $k_L a$ ) for a specific gas-liquid system. Values of these characteristics needed for modelling of hydrodynamics in large-scale units has to be therefore predicted on the basis of laboratory (small-scale) data using a suitable approximative scaling-up procedure<sup>11</sup>.

#### LIST OF SYMBOLS

$a$	specific interfacial area
$d_s$	Sauter mean bubble diameter
$d_0$	diameter of plate holes
$D_K$	diameter of reactor
$D_L$	diffusivity of gas dissolved in liquid
$Fr$	Froude number
$g$	gravitational acceleration
$H_0$	clear liquid height
$k_L a$	volumetric mass transfer coefficient
$k_L$	liquid side mass transfer coefficient
$n$	number of holes on the plate
$n_B$	number of bubbling holes on the plate
$u_0$	gas velocity in plate holes
$We$	Weber number
$w_G$	superficial gas velocity
$\epsilon_G$	relative gas holdup in the bed
$\phi$	relative free plate area
$\mu$	dynamic viscosity
$\nu$	kinematic viscosity
$\rho$	density
$\sigma$	surface tension
$\Phi$	constant, Eq. (2)
$\eta$	concentration of holes on the plate

#### Subscripts

G	gas phase
L	liquid phase
o	quantities related to the plate hole

#### REFERENCES

1. Zahradník J., Kaštánek F.: This Journal 43, 216 (1978).
2. Zahradník J.: This Journal 44, 348 (1979).
3. Zahradník J., Kaštánek F.: Chem. Eng. Commun. 3, 413 (1979).

4. Zahradník J., Kaštánek F., Rylek M.: *This Journal* 39, 1403 (1973).
5. Líněk V., Beneš P.: *Biotechnol. Bioeng.* 19, 741 (1977).
6. Mersmann A.: *Ger. Chem. Eng.* 1, 1 (1978).
7. Gerstenberg H.: *Chem.-Ing.-Tech.* 51, 208 (1979).
8. Kaštánek F.: *This Journal* 42, 2491 (1977).
9. Schügerl K., Lücke J., Oels U.: *Advan. Biochem Eng.* 7, 1 (1977).
10. Bach F. H., Pilhofer T.: *Ger. Chem. Eng.* 1, 270 (1978).
11. Kaštánek F., Zahradník J., Kratochvíl J., Rylek M.: *Chem. Eng. Sci.* 35, 456 (1980).
12. Hugmark G. A.: *IEC Proc. Des. Dev.* 6, 218 (1967).
13. Hikita H., Asai S.: *Chem. Eng. J.* 20, 59 (1980).
14. Voigt J., Hecht V., Schügerl K.: *Chem. Eng. Sci.* 35, 1317 (1980).
15. Kaštánek F., Nývlt V., Rylek M.: *This Journal* 39, 529 (1974).

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